FORESHOCK, MAIN SHOCK, AND LARGER AFTERSHOCKS OF THE BORREGO MOUNTAIN EARTHQUAKE[1]

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ABSTRACT

The Borrego Mountain earthquake, magnitude 6.4, occurred at 02:28:59.1 G.m.t. on April 9, 1968 and has been assigned a hypocenter at 33°11.4′ N., 116°07.7′ W., h=11.1 km. The focal-mechanism solution indicates right-lateral slip on a fault striking N. 48° W. and dipping 83° NE., which is consistent with the field observations of faulting and the regional tectonic framework. A single foreshock of magnitude 3.7 preceded the main shock by one minute, but no other precursory activity has been identified. During the year following the event, 135 aftershocks of magnitude 3.0 and greater have been identified and located, outlining a broad zone of activity centered on but displaced 2–3 km northeast of the 33-km-long surface rupture on the Coyote Creek fault. Fracturing at depth during the aftershock period evidently occurred throughout the width of the San Jacinto fault zone, but initial surface faulting was localized along the Coyote Creek fault at the zone's southwestern margin. The area of aftershock activity enlarged progressively with time, and the region of the original epicenter became relatively inactive late in the aftershock period, leading to a doughnut-shaped epicentral distribution of late aftershocks. Inasmuch as the epicenter of the main shock was roughly midway along the zone of aftershock activity, the faulting presumably was bilateral. This kind of faulting is unusual in California.

INTRODUCTION

The earthquake of magnitude 6.4 that occurred near Borrego Mountain, Calif., was the largest earthquake to occur in the conterminous United States since 1959. It ranks among the larger shocks recorded in the southern California region since the establishment of modern seismographic stations (fig. 5). The earthquake was preceded by a minor foreshock, was followed by a series of aftershocks that lasted for several months, and was accompanied by right-lateral surface faulting along a 33-km segment of the Coyote Creek fault (Clark, "Surface Rupture Along the Coyote Creek Fault," this volume). Probably the most surprising and significant phenomenon associated with the earthquake was the triggering of small displacements on a number of distant faults far outside the aftershock area (Allen and others, this volume).

The Borrego Mountain earthquakes occurred in a fortunate location with respect to the distribution of seismographic stations that were in operation at the time of the main shock. Seven stations of the Caltech

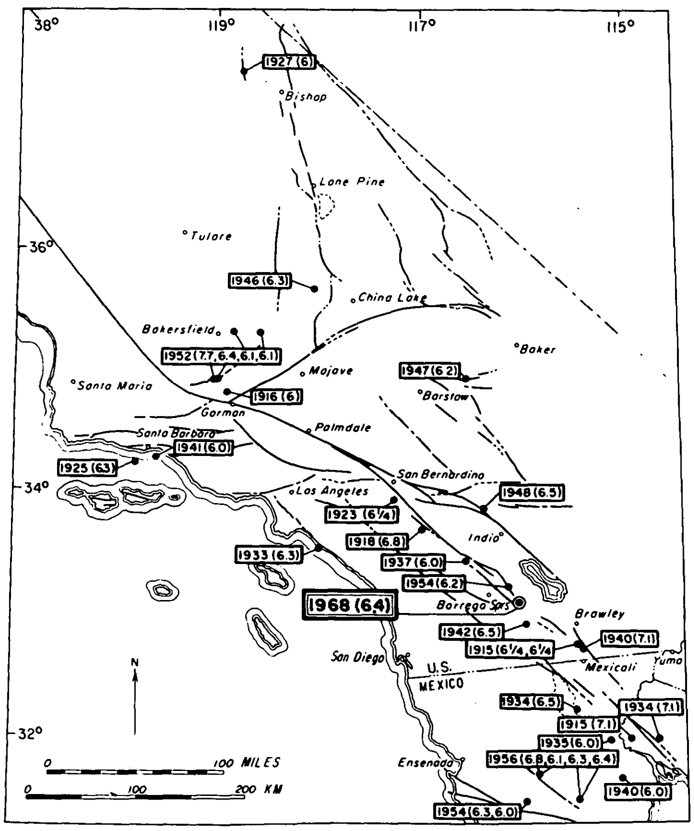

FIGURE 5. — Epicenter of the 1968 Borrego Mountain earthquake in relation to major faults, and epicenters of other earthquakes of magnitude 6.0 and greater in southern California since 1912. (Adapted from Allen and others, 1965.)

[1]Contribution No. 1953, California Institute of Technology, Division of Geological and Planetary Sciences, Pasadena, Calif.

network surrounded the epicenter within 150 km, including a temporary trailer-mounted station 47 km distant at Obsidian Butte (OBB, fig. 6). Thus we

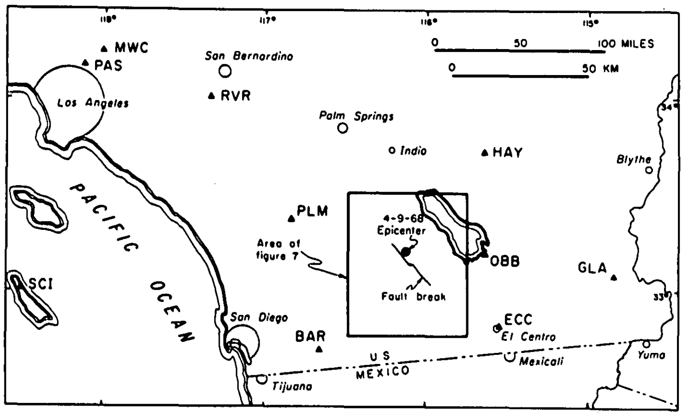

FIGURE 6. — Location of Caltech seismographic stations (solid triangles) that were operating at the time of the Borrego Mountain earthquake. The area of the detailed epicenter map (fig. 7) is also shown.

have some confidence in the epicentral locations of most of the larger shocks of the series, although depth control was minimal until the time that the first portable units were installed in the epicentral area.

Although the main shock occurred in the evening (6:29 p.m., April 8, 1968, local time), rapid computer location of the epicenter using the Caltech telemetered array allowed immediate planning of a field-recording program. Several field crews were dispatched to the epicentral area before 9:00 p.m., and the first backpack-mounted seismograph was installed within 5 km of the epicenter shortly after midnight. By 3:00 a.m., the first film-recording trailer-mounted unit was in operation at Ocotillo Wells (OCT, fig. 7), and two more trailer units were installed the next day (ELW and FCR, fig. 7) (table 1). These trailer units operated up to and following

TABLE 1. — *Caltech trailer-mounted stations in operation during the Borrego Mountain aftershock period*

Station		Lat (N.)	Long (W.)	Period of operation (G.m.t)
Code	Name			
ELW	Ella Wash	33°17.20′	116°08.95′	4–10–68 (03:05) to 5–13–68
FCR	Fish Creek Range	33°01.82′	116°03.50′	4– 9–68 (19:23) to 6–12–68
OBB	Obsidian Butte	33°10.15′	115°38.17′	1– 8–68 to 9–15–68
				12–17–68 to 12–20–68
				3–21–69 to 6–14–69
OCT	Ocotillo Wells	33°09.60′	116°09.04′	4– 9–68 (10:12) to 6–11–68

the time that the much more extensive U.S. Geological Survey array began yielding high-precision hypocentral information on April 12 (Hamilton, this volume). This paper describes the events that took place prior to the installation of the U.S. Geological Survey array and summarizes the larger aftershocks

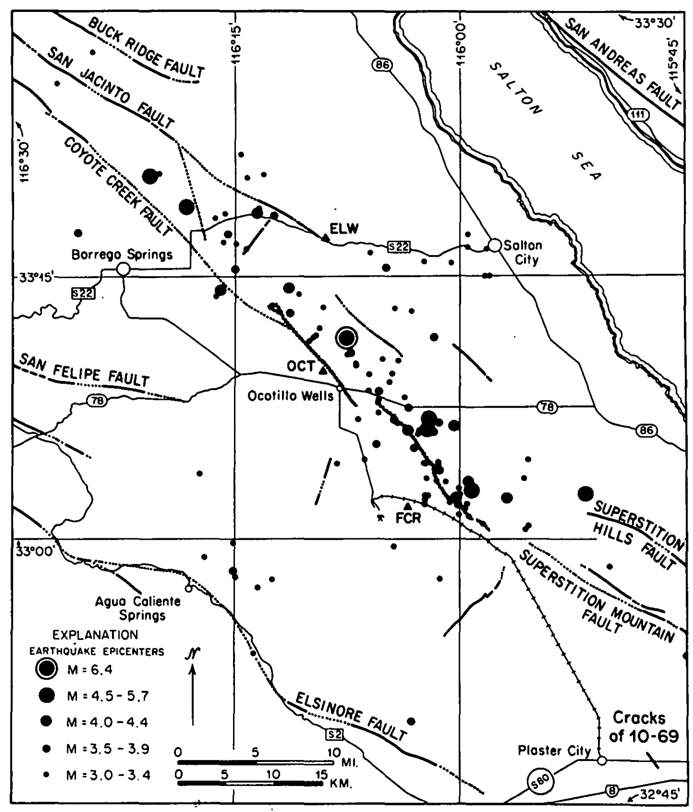

FIGURE 7. — Epicenters of shocks of magnitude 3.0 and greater that occurred between April 9, 1968 and April 28, 1969. All shocks listed in table 2 are included, except for those with "D"-quality locations. Of the 126 epicenters shown, 69 were located by Caltech and 57 by the U.S. Geological Survey (Hamilton, this volume). Heavy solid lines are accurately located faults; dotted lines are concealed faults; the zigzag line is the approximate trace of the 1968 surface break along Coyote Creek fault (Clark, "Surface Rupture Along the Coyote Creek Fault," this volume).

that occurred during the entire aftershock period, including those aftershocks that followed the removal of the U.S. Geological Survey equipment in June.

ACKNOWLEDGMENTS

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SEISMIC HISTORY

The San Jacinto fault zone, of which the Coyote Creek fault is a member (Sharp, this volume), has been the locus of repeated moderate seismic activity within the entire historical record (Allen and others, 1965). Assuming that the zone extends southeast to the Gulf of California, at least 10 shocks of magnitude 6–7 have occurred along this line since 1912, and the fault zone is better delineated by seismic activity in this magnitude range than is any other individual fault in California. Many of the epicenters have been about equidistant along the fault (fig. 5), and the 1968 epicenter lies roughly midway between the epicenters of the 1942 Lower Borrego Valley earthquake (M=6.5) and the 1954 Santa Rosa Mountains earthquake (M=6.2).

HYPOCENTRAL DETERMINATIONS

Table 2 is a listing of all shocks of magnitude (M_L) 3.0 and greater that occurred from the time of the foreshock at 0227 G.m.t. on April 9, 1968 to the time of the Coyote Mountain earthquake on April 28, 1969, about 1 year later. The list was terminated with the Coyote Mountain earthquake

TABLE 2. — *Earthquakes of magnitude 3.0 and greater in the area from 32°45′ to 33°30′ N. and from 115° to 116°30′ W. from April 9, 1968 through April 28, 1969*

["Q" indicates quality, as discussed in text. Depths indicated by "R" were restricted to that depth in the computer solution. Source "T" is California Institute of Technology; source "G" is U.S. Geological Survey. Quadrangle names are those of USGS 15-minute quadrangles. All magnitudes are assigned by Pasadena. A-, B-, and C-quality epicenters are shown in the maps of figures 7 and 9]

Time				Lat (N.)	Long (W.)	Quality	Magnitude	Depth (ft)	Source	Quadrangle
Yr	Mo	Da	H M S							
68	04	09	02 27 36.7	33 10.5	116 07.3	B	3.7	4.8	T	Borrego Mountain
68	04	09	02 28 59.1	33 11.4	116 07.7	A	6.4	11.1	T	Do.
68	04	09	02 33 09.0	33 10.0	116 07.0	D	4.3	......	T	Do.
68	04	09	02 36 47.0	33 10.0	116 07.0	D	3.7	......	T	Do.
68	04	09	02 39 30.0	33 10.0	116 07.0	D	4.4	......	T	Do.
69	04	09	02 44 48.0	33 10.0	116 07.0	D	3.6	......	T	Do.
68	04	09	02 47 48.5	33 05.3	116 05.7	C	3.7	10.0R	T	Do.
68	04	09	03 01 43.0	33 10.0	116 07.0	D	3.9	......	T	Do.
68	04	09	03 03 53.5	33 06.8	116 02.2	C	5.2	5.0R	T	Do.
68	04	09	03 08 39.9	32 49.6	116 03.3	C	3.5	10.0R	T	Carrizo Mountain
68	04	09	03 22 22.0	33 10.0	116 07.0	D	3.3	......	T	Borrego Mountain
68	04	09	03 48 10.3	33 06.3	116 02.2	C	4.7	4.8R	T	Do
68	04	09	03 58 36.0	33 03.3	115 59.6	C	4.3	7.9	T	Kane Spring
68	04	09	04 05 05.3	33 12.8	116 11.3	C	3.7	5.0R	T	Borrego Mountain
68	04	09	04 15 47.5	33 06.7	116 01.5	B	3.6	5.3R	T	Do.
68	04	09	04 29 56.9	33 09.4	116 04.7	C	3.2	10.0R	T	Do.
68	04	09	04 46 50.0	33 10.0	116 07.0	D	3.0	......	T	Do.
68	04	09	05 00 54.7	33 03.9	116 01.4	B	3.7	1.3	T	Do.
68	04	09	07 20 47.2	32 59.6	116 04.6	C	3.2	5.0R	T	Carrizo Mountain
68	04	09	07 35 46.3	33 11.5	116 01.9	C	3.5	2.8	T	Borrego Mountain
68	04	09	07 36 23.0	33 10.0	116 07.0	D	3.6	......	T	Do.
68	04	09	07 38 21.7	33 09.9	116 07.0	C	3.1	10.0R	T	Do.
68	04	09	07 40 46.8	33 07.2	116 05.5	C	3.2	10.0R	T	Do.
68	04	09	08 00 38.5	33 06.4	116 00.4	C	4.0	4.2R	T	Do.
68	04	09	08 02 26.0	33 10.0	116 07.0	D	3.5	......	T	Do.
68	04	09	08 27 22.6	33 14.2	116 16.2	B	3.6	2.8	T	Borrego
68	04	09	08 43 52.1	33 20.8	116 13.0	B	3.4	7.6	T	Rabbit Peak
68	04	09	09 26 26.1	33 05.2	116 03.1	B	3.8	3.0	T	Borrego Mountain
68	04	09	09 38 33.0	33 14.1	116 16.0	C	4.0	5.2	T	Borrego
68	04	09	10 42 08.9	33 10.6	116 07.7	C	3.1	10.0R	T	Borrego Mountain
68	04	09	11 11 49.6	33 13.1	116 09.1	C	3.1	10.0R	T	Do.
68	04	09	11 17 54.5	33 06.2	116 03.6	B	4.0	4.8R	T	Do.
68	04	09	12 20 01.0	33 15.4	116 15.0	B	3.6	3.4	T	Rabbit Peak
68	04	09	12 24 28.0	33 10.0	116 07.0	D	3.0	......	T	Borrego Mountain
68	04	09	15 25 17.7	33 08.1	116 03.8	C	3.2	10.0R	T	Do.
68	04	09	16 20 56.3	33 13.2	116 12.5	C	3.4	10.0R	T	Do.
68	04	09	17 25 36.7	33 07.4	116 03.5	B	3.5	—0.6	T	Do.
68	04	09	18 31 03.8	33 18.9	116 18.3	B	4.7	12.6	T	Clark Lake
68	04	09	19 32 46.1	33 02.2	116 02.5	C	3.0	10.0R	T	Borrego Mountain
68	04	09	21 39 04.1	33 06.9	116 06.9	C	3.3	5.0R	T	Do.
68	04	10	00 01 11.3	33 06.8	116 04.5	B	3.7	2.2	T	Do.
68	04	10	00 17 41.6	33 10.2	116 05.2	C	3.3	10.0R	T	Do.
68	04	10	04 05 12.6	33 06.6	116 04.2	C	3.4	10.0R	T	Do.
68	04	10	05 26 28.0	33 01.5	116 00.1	C	3.2	10.0R	T	Do.
68	04	10	05 33 52.7	33 04.7	116 06.3	C	3.1	10.0R	T	Do.
68	04	10	06 05 12.6	33 13.8	116 16.3	C	3.2	10.0R	T	Borrego
68	04	10	09 22 57.5	33 08.3	116 05.4	C	3.5	10.0R	T	Borrego Mountain
68	04	10	13 33 04.9	33 15.5	116 05.0	B	3.9	0.4	T	Rabbit Peak
68	04	10	19 11 06.3	33 13.9	116 10.8	B	3.3	4.6	T	Borrego Mountain
68	04	10	23 57 58.0	33 02.7	116 00.1	C	3.0	10.0R	T	Do.

TABLE 2. — *Earthquakes of magnitude 3.0 and greater in the area from 32°45′ to 33°30′ N. and from 115° to 116°30′ W. from April 9, 1968 through April 28, 1969*—Continued

Time				Lat (N.)	Long (W.)	Quality	Magnitude	Depth (ft)	Source	Quadrangle
Yr	Mo	Da	H M S							
68	04	11	01 12 24.1	33 13.0	116 03.3	B	3.2	5.2R	T	Borrego Mountain
68	04	11	11 00 24.4	33 11.3	116 10.0	C	3.0	10.0R	T	Do.
68	04	11	15 56 32.0	33 10.0	116 07.0	D	3.5	......	T	Do.
68	04	11	15 56 57.0	33 10.0	116 07.0	D	3.7	......	T	Do.
68	04	11	17 01 51.0	32 58.1	116 15.1	B	3.5	5.2	T	Mount Laguna
68	04	11	22 28 23.7	33 06.2	116 02.9	B	3.4	—0.8R	T	Borrego Mountain
68	04	12	01 37 01.0	33 10.1	116 04.2	A	3.4	5.0	G	Do.
68	04	12	11 29 50.2	33 18.3	116 16.3	C	3.1	10.0R	T	Clark Lake
68	04	12	13 42 49.5	33 16.9	116 15.8	A	3.3	2.6	G	Do.
68	04	12	15 26 45.5	33 01.0	115 58.6	A	3.2	7.9	G	Kane Spring
68	04	12	21 02 59.1	33 04.4	116 02.6	A	3.1	6.8	G	Borrego Mountain
68	04	13	01 23 49.3	33 16.6	116 14.2	A	3.3	1.3	G	Rabbit Peak
68	04	13	08 27 05.9	33 06.0	116 02.9	A	3.2	1.5	G	Borrego Mountain
68	04	13	10 05 18.2	33 03.3	116 01.0	A	3.2	2.4	G	Do.
68	04	13	18 23 24.5	33 06.4	116 03.6	A	3.3	8.7	G	Do.
68	04	14	01 23 04.2	32 57.8	116 15.0	A	3.2	11.2	G	Mount Laguna
68	04	14	01 26 18.3	33 08.5	116 05.9	A	3.0	4.9	G	Borrego Mountain
68	04	14	12 55 58.7	33 14.2	116 11.4	A	4.3	10.8	G	Do.
68	04	14	16 46 30.4	33 09.4	116 06.0	A	3.0	4.9	G	Do.
68	04	15	10 07 11.6	33 18.9	116 13.3	A	3.3	3.0	G	Rabbit Peak
68	04	15	12 28 07.5	33 17.4	116 15.6	A	3.5	3.0	G	Clark Lake
68	04	15	21 56 50.3	33 02.7	115 59.3	A	3.4	7.3	G	Kane Spring
68	04	15	22 07 06.1	33 02.9	115 59.0	A	3.3	8.2	G	Do.
68	04	16	03 30 30.0	33 02.9	115 59.2	A	4.8	8.3	G	Do.
68	04	17	02 43 47.5	33 03.2	115 59.6	A	3.7	7.9	G	Do.
68	04	17	03 14 25.8	33 14.0	116 11.3	A	3.4	11.4	G	Borrego Mountain
68	04	17	11 16 26.9	33 16.8	116 14.9	B	3.0	5.0	T	Rabbit Peak
68	04	20	09 37 37.6	33 22.0	116 14.6	A	3.2	10.1	G	Do.
68	04	24	09 03 12.5	33 08.0	116 05.3	A	3.4	5.7	G	Borrego Mountain
68	04	24	22 09 54.2	33 03.4	116 01.7	A	3.0	1.9	G	Do.
68	04	27	09 32 30.0	33 11.9	116 09.4	A	3.0	5.1	G	Do.
68	04	27	19 09 10.4	33 15.1	115 58.3	A	3.1	0.3	G	Durmid
68	04	29	00 52 51.2	33 06.9	116 04.7	A	3.0	3.3	G	Borrego Mountain
68	05	01	23 53 37.2	33 15.1	115 58.0	A	3.0	0.3	G	Durmid
68	05	02	00 55 30.0	33 17.4	116 15.6	A	3.5	6.6	G	Clark Lake
68	05	02	23 19 26.0	33 09.0	116 04.8	A	3.1	7.6	G	Borrego Mountain
68	05	03	12 15 40.3	33 01.8	115 59.8	A	3.1	3.8	G	Kane Spring
68	05	06	10 53 36.9	33 02.0	116 00.1	A	3.5	9.2	G	Borrego Mountain
68	05	06	17 31 47.6	33 02.4	115 56.9	A	4.0	6.7	G	Kane Spring
68	05	07	07 56 37.8	33 16.3	116 06.0	A	3.3	2.9	G	Rabbit Peak
68	05	08	16 23 38.1	33 11.5	116 09.8	A	3.3	3.1	G	Borrego Mountain
68	05	08	22 30 06.3	33 10.7	116 07.6	A	3.0	6.9	G	Do.
68	05	09	10 21 46.2	33 06.1	116 01.9	A	3.6	7.3	G	Do.
68	05	10	04 32 25.2	33 02.1	116 02.4	A	3.4	5.3	G	Do.
68	05	10	05 28 07.8	33 02.0	116 02.4	A	3.3	4.8	G	Borrego Mountain
68	05	11	08 10 04.0	33 02.4	116 00.3	A	4.2	8.8	G	Do.
68	05	11	08 46 03.6	33 02.4	116 00.3	A	3.5	8.5	G	Do.
68	05	11	10 38 31.7	33 16.7	115 58.1	A	3.0	1.3	G	Durmid
68	05	12	14 24 16.3	33 27.7	116 24.4	A	3.3	6.3	G	Clark Lake
68	05	13	18 33 52.2	33 18.6	116 15.7	A	3.3	8.5	G	Do.
68	05	20	04 04 17.9	33 04.3	116 08.2	A	3.2	8.7	G	Borrego Mountain
68	05	21	14 34 31.3	33 04.2	116 01.6	A	3.2	1.1	G	Do.
68	05	21	23 19 39.4	33 02.1	115 59.6	A	3.0	4.8	G	Kane Spring
68	05	22	13 26 55.4	33 18.6	116 13.4	A	4.4	7.5	G	Rabbit Peak
68	05	26	06 46 28.1	33 02.4	116 02.4	A	3.2	4.4	G	Borrego Mountain
68	05	31	00 29 02.1	33 03.6	115 55.8	A	3.2	3.5	G	Kane Spring
68	06	02	00 02 43.9	33 02.6	116 00.2	A	3.3	7.2	G	Borrego Mountain
68	06	03	09 10 22.4	33 11.7	116 09.7	A	3.3	7.7	G	Do.
68	06	04	03 48 19.7	33 02.4	116 02.3	A	3.2	5.1	G	Do.
68	06	06	09 12 02.0	33 00.6	115 55.7	A	3.2	6.4	G	Kane Spring
68	06	06	13 18 04.9	33 00.8	115 55.6	A	3.1	7.6	G	Do.
68	06	08	21 37 00.9	33 15.9	116 02.5	A	3.1	1.3	G	Rabbit Peak
68	06	09	14 20 15.6	33 16.8	115 59.5	A	3.1	2.9	G	Durmid
68	06	09	14 48 29.6	33 04.6	115 55.5	A	3.0	5.1	G	Kane Spring
68	06	11	05 32 17.3	33 20.9	116 20.0	A	3.1	10.1	G	Clark Lake
68	06	14	16 38 12.3	33 02.1	116 00.7	B	3.1	5.0R	T	Borrego Mountain
68	06	26	21 35 11.3	33 17.5	115 59.4	B	3.0	5.0R	T	Durmid
68	06	26	21 38 23.3	33 15.8	116 00.7	B	3.1	—0.6	T	Rabbit Peak
68	08	03	10 02 18.7	32 57.7	116 12.7	B	3.4	2.3	T	Carrizo Mountain
68	08	12	07 07 07.7	32 57.8	116 01.4	B	3.0	4.5	T	Do.
68	08	14	09 19 21.8	33 18.5	116 12.5	B	3.7	—0.7	T	Rabbit Peak
68	08	22	19 35 18.7	32 58.3	115 50.1	C	3.3	—2.0	T	Plaster City
68	09	29	04 06 07.4	33 06.6	116 01.6	C	3.3	5.0R	T	Borrego Mountain
68	10	07	14 15 21.6	33 17.4	116 25.6	C	3.6	10.0R	T	Clark Lake
68	10	19	03 50 18.6	33 01.4	115 59.4	B	3.0	—1.3	T	Kane Spring
68	10	23	19 54 42.7	33 04.3	116 02.4	B	3.1	—1.1	T	Borrego Mountain
68	10	28	11 51 55.7	33 04.4	116 01.5	B	3.2	—0.8	T	Do.
68	10	28	23 53 13.0	32 59.0	116 17.0	B	3.1	10.0R	T	Mount Laguna
68	10	31	04 04 44.0	33 03.5	116 02.2	B	3.1	10.0R	T	Borrego Mountain
68	11	05	11 50 50.6	33 26.0	116 26.8	B	3.0	6.6	T	Clark Lake
68	11	10	07 42 00.1	33 13.1	116 04.3	B	3.0	10.0R	T	Borrego Mountain
68	11	23	10 33 50.6	33 20.7	116 14.1	C	3.2	10.0R	T	Rabbit Peak
68	11	28	02 29 58.0	32 59.8	116 15.1	C	3.2	10.0R	T	Mount Laguna
68	12	14	22 30 30.3	32 53.6	116 13.8	B	3.4	10.0R	T	Carrizo Mountain
68	12	17	22 53 51.2	33 02.7	115 51.8	B	4.7	8.0R	T	Kane Spring
69	01	30	16 08 51.8	33 03.8	116 17.4	C	3.1	—2.0	T	Borrego
69	03	29	06 57 26.8	32 57.2	116 13.6	C	3.4	—2.0	T	Carrizo Mountain
69	04	28	23 20 42.9	33 20.6	116 20.8	B	5.8	20.0R	T	Clark Lake

(M=5.8) because it was larger than any earlier aftershock; it occurred somewhat farther northwest than most earlier aftershocks (fig. 7), and it had numerous local aftershocks of its own. Table 2 is thought to represent a relatively homogeneous coverage of earthquakes of magnitude 3.0 and greater during the 1-year period, except for a period of about 2 hours following the main shock, when some small aftershocks could have been missed because of the congested records. For the purpose of this study, aftershocks were arbitrarily assumed to include all shocks that occurred within the area of figure 7. This area includes the following U.S. Geological Survey 15-minute quadrangles (from left to right, top to bottom, in fig. 7): Clark Lake, Rabbit Peak, Durmid, Borrego, Borrego Mountain, Kane Spring, Mt. Laguna, Carrizo Mountain, and Plaster City.

The establishment of precise time correction factors for the permanent stations of the Caltech network was made possible by the presence of the 20-station USGS (U.S. Geological Survey) array in the epicentral area (Hamilton, this volume) and by the calibration of this array with three widely separated explosions (Hamilton, 1970). Fifty-five of the largest USGS-located shocks that occurred during the 2-month period between April 12, 1968 and June 12, 1968 were used to establish station time corrections to be applied to the Caltech computer-location program (Nordquist, 1962). Average time corrections for P-arrivals of the aftershocks at the nearby stations are given in table 3; only those stations with time corrections shown were used in the routine

TABLE 3. — *Borrego Mountain earthquake data for stations of the Pasadena network*

Station Code	Station Name	P-wave arrival time, main shock (G.m.t.) h m s	Time correction, main shock (s)	Time correction, aftershocks (s)	Distance to hypocenter, main shock (km)	First motion, main shock (quality)
BAR	Barrett	02:29:11.3	+0.3	+0.1	76.8	D
CLC	China Lake	44.1	....	....	320.5	....
CWC	Cottonwood	54.3	....	....	401.7	....
ECC	El Centro	10.7	.0	....	70.2	C
ELW	Ella Wash (temporary)	......	....	− .4	15.8	....
FCR	Fish Creek Range (temporary)	......	....	− .2	21.9	....
FTC	Fort Tejon	44.2	....	....	315.9	D
GLA	Glamis	17.6	+1.2	+ .7	122.9	C
GSC	Goldstone	34.4	+ .9	+ .2	242.0	D
HAY	Hayfield	11.7	− .5	− .5	74.2	D
ISA	Isabella	47.6	....	....	348.4	D
MWC	Mount Wilson	30.8	− .1	−1.1	212.0	C
OBB	Obsidian Butte (temporary)	07.5	− .6	− .6	47.3	....
OCT	Ocotillo Wells (temporary)	......	....	− .3	11.9	C
PLM	Palomar	11.1	− .2	− .1	41.8	C
PAS	Pasadena	30.0	....	−1.1	216.8	C
RVR	Riverside	22.0	+ .9	+ .5	146.4	D
SCI	San Clemente Island	32.1	+ .6	+ .2	226.7	C
SBC	Santa Barbara	49.2	....	....	....	C
SWM	Sawmill	40.9	....	....	282.6	....
SYP	Santa Ynez Peak	52.0	....	....	385.4	C
TIN	Tinemaha	02:30:04.2	....	....	469.0	D
WDY	Woody	02:29:50.4	....	....	373.6	D

locations of aftershocks. These corrections were used to determine the Caltech hypocenters listed in table 2, except for the main shock, which is discussed separately below. Even with these corrections, not all shocks could be assigned good hypocenters, mainly because of poor arrivals masked by contemporaneous events or wind noise or because of sporadic station failures. "B" quality epicenters are thought to be accurate within 5 km, "C" quality within 15 km, and "D" quality greater than 15 km, although the quality assignments in table 2 are generally conservative. "A" quality locations, such as those of the main shock and the U.S. Geological Survey epicenters, are the subject of special investigation and individual error assignments. A measure of the accuracy of hypocentral determinations from the Caltech stations alone ("T" source in table 2), when the above corrections are applied, can be determined by comparing the depths assigned to all Caltech "B" hypocenters that were independently located by both networks. The average difference in depth assignments is 2.0 km; this amount of difference suggests that most of the "B" locations in table 2 are indeed accurate to within 5 km and many are much more accurate.

FORESHOCK ACTIVITY

A single foreshock of magnitude 3.7 preceded the main shock by about 1 minute, and its hypocenter can be considered identical with that of the main shock within the limits of location error. Perhaps the most significant feature of the foreshock activity, however, is the complete absence of any other foreshocks or preceding regional activity. Records of the 47-km-distant station at Obsidian Butte, for example, show no hint of any other earthquakes in the epicentral region within the previous few hours and days, and the general level of activity at this station had been unusually low during the preceding 4 months. Within the year preceding the main Borrego Mountain shock, only two earthquakes that might be considered within the zone of subsequent aftershock activity along the Coyote Creek fault are listed in the Caltech Local Bulletin.

MAIN SHOCK

LOCATION

The main shock was located by using correction factors that were based on arrival-time residuals of only the 11 largest shocks that were recorded by both the USGS and Caltech networks — all of these shocks exceeded magnitude 3.4. The restriction to larger shocks permits a more direct comparison with the main shock, particularly for the more distant stations. These time corrections, as well as the

P-wave arrival times used in the solution, are given in table 3; only those stations with time corrections shown in table 3 were used in this solution. The computed hypocenter is 33°11.4′ N., 116°07.7′ W., h=11.1 km. Standard errors in the computer solution of the x, y, and z components are 0.65, 0.96, and 2.01 km, respectively, but these are felt to be unrealistic in view of the somewhat arbitrary assignment of correction factors. On the basis of numerous attempts to locate the epicenter using a wide variety of assumptions and models, we believe that the computed epicenter is correct to within 3 km, but because the nearest station (OBB) is 47 km away, depth control is poor. Nevertheless, the comparatively large hypocentral depth of the main shock relative to that of most aftershocks is consistent with the observations of Hamilton (this volume), who notes that all A- and B-quality USGS hypocenters of shocks exceeding magnitude 3.4 are at depths below 6 km; their average depth is 8.06 km, compared to an average depth of 4.97 for the hypocenters of all A- and B-quality aftershocks listed in table 8.

MAGNITUDE

A local magnitude (M_L) of 6.4 has been assigned to the Borrego Mountain main shock by C. F. Richter, who used records of seven widely spaced stations of the Pasadena network. Most of the Wood-Anderson torsion seismometers of the network were driven off-scale by the main shock; to determine the magnitude it was necessary to compare the main shock with a well-recorded aftershock by using low-magnification seismometers (for example, 100×). The magnitude 5.2 aftershock of 0304, April 9, was recorded on 12 torsion instruments and on 17 low-magnification instruments that remained on-scale during the main shock; comparing the amplitudes on the various records is consistent with a magnitude assignment of 6.4 for the main shock. Berkeley reported a magnitude of 7.1–7.2 for the same shock (Niazi and others, 1969), and the U.S. Coast and Geodetic Survey PDE[2] card reported a magnitude of 6.1 from the magnitude-determination system in use at that time.

FOCAL MECHANISM

The focal mechanism for the Borrego Mountain main shock is shown in figure 8. The focal mechanism was solved by following the technique of Sykes (1967); a focal depth of 10 km and a crustal velocity of 6.0 km per sec were assumed. The two nodal planes are both relatively well defined and must be near vertical. It is reasonable to assume that the fault is represented by the nodal plane that strikes

[2]Preliminary determination of epicenter.

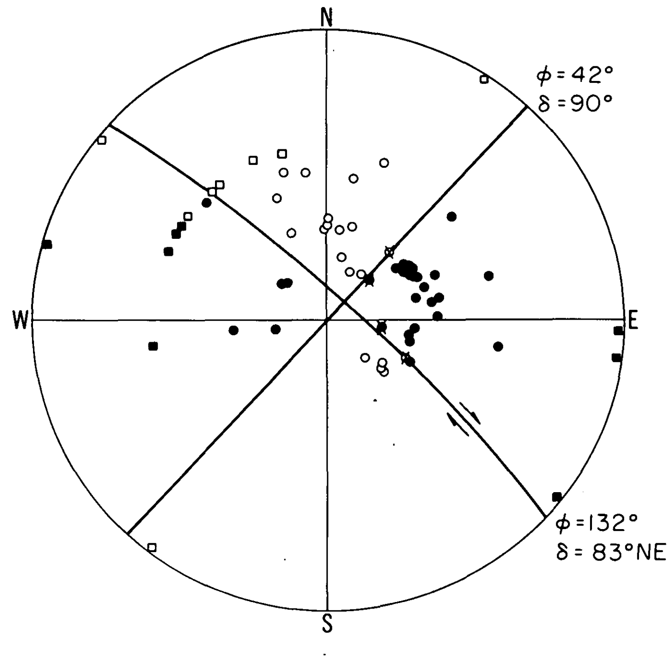

FIGURE 8. — Focal-mechanism solution for the Borrego Mountain main shock. Diagram is an equal-area projection of the lower hemisphere of the radiation field. Solid symbols represent compressions; open symbols, dilatations; square symbols, stations of the Pasadena network; circular symbols, distant stations of the Worldwide Standard Seismograph Network (WWSSN) and Canadian network; crosses, wave character indicating stations near nodal plane. θ and δ are strike and dip of nodal planes, and arrows indicate sense of shear on the plane chosen as the fault plane.

northwest and dips steeply to the northeast, at least 80°, and that has a right-lateral displacement of almost purely strike-slip character. The only inconsistencies in the solution are from nearby stations of the Pasadena network (table 3; square symbols in fig. 8), where there is a discrepancy between the first motions at Fort Tejon and Riverside compared with those at Berkeley. The more distant long-period arrival at Berkeley, which was clearly compressional, is given precedence in the solution. Although 15 of the 17 nearby stations are clearly consistent with the more distant stations, minor inconsistencies in the nearby stations are not surprising, particularly in view of the very complicated crustal structure in the epicentral region. Stations of the Pasadena network that are presumed to have received direct P arrivals are arbitrarily plotted at the edge of the net in figure 8.

The fault-plane strike of 132° (N. 48° W.) corresponds within a few degrees to the trend of major aftershock activity (fig. 7) and to the trend of surface faulting (Clark, "Surface Rupture Along the Coyote Creek Fault," this volume). The steep dip, however, seems to preclude the possibility that the apparent offset of the line of major aftershocks 2–3 km northeast of the trace of surface fracturing can be caused by dip of the fault surface. Such a hypothesis would require a much shallower dip of the fault plane (for example, 70°) than is permitted by the focal-mechanism solution; furthermore, this hypothesis is not suggested by most of Hamilton's vertical cross sections (fig. 16).

Late in the aftershock period, a number of events occurred near the southeastern extremity of faulting that may be related to the creep history of surface displacement. During the aftershock period, little or no creep occurred on the northwestern segment of the surface trace (north of Highway 78), but considerable creep took place along the southeastern segment (Clark, "Surface Rupture Along the Coyote Creek Fault," this volume). When one compares the relative aftershock activity in the two areas, it seems reasonable that at least some of the creep in the southeastern segment may have been associated with the much more numerous aftershocks in this area, such as the increased activity that took place here shortly after April 14 (fig. 9C).

EPICENTRAL DISTRIBUTION OF AFTERSHOCKS AS A FUNCTION OF TIME

Inasmuch as it was not possible to assign accurate epicenters to a number of larger aftershocks that occurred within a few hours of the main event (table 2), arguments as to possible changes of aftershock activity with time are necessarily somewhat limited. Within 2 hours of the main shock, it is likely that aftershocks had occurred essentially over the entire length of the surface rupture as it was mapped in the days following the event. (Note, however, that most of the initial epicenters listed in table 3 are of C-quality.) Nevertheless, there is a definite suggestion of gradual enlargement of the zone of aftershock activity in the days and weeks following the earthquake. Figure 9 shows the distribution of epicenters during four successive time periods having roughly equal numbers of shocks of magnitude 3.0 and above, and the progressive expansion of areal activity is obvious, particularly late in the aftershock period (fig. 9D). For example, most of the numerous events near the southeast end of the fault trace, near 33°02′ N. 116°00′ W., occurred after April 14 (fig. 9C). Likewise, the two outlying areas of minor activity situated symmetrically with respect to the fault trace near Salton City and Agua Caliente Springs (fig. 7) became active primarily after April 27 (fig. 9D). Two of the largest aftershocks occurred near the extreme ends of the aftershock zone many months after the main event; these are the Coyote Mountain earthquake (M=5.8) of April 28, 1969, which may not be an aftershock in the usual sense, and the shock of December 17, 1968 (M=4.7), which lies almost on the trace of the Superstition Hills fault (fig. 7, 9D). It is also significant that during the late period, when aftershocks were occurring over a wide area, almost no shocks exceeding magnitude 3.0 occurred in the area of original surface faulting except at its southeast end. Thus, the late-period aftershock distribution takes on almost a doughnut shape.

TECTONIC IMPLICATIONS

The hypocentral distribution of the Borrego Mountain earthquakes leads to several conclusions of tectonic significance: (1) Aftershocks are not limited to a single fault plane; instead they are distributed over a wide zone — in sharp contrast to the aftershock distribution of the Parkfield-Cholame earthquakes (Eaton, 1967); (2) the zone of most concentrated aftershock activity parallels but is somewhat northeast of the line of surface rupture along the Coyote Creek fault; (3) the epicenters of all shocks above magnitude 4.5, including that of the main shock, seem to lie along a single line 2–3 km northeast of the Coyote Creek fault trace, with the exception of the shock of December 17, 1968 that is near the Superstition Hills fault; (4) the zone of rupturing at depth evidently extends farther northwest than does the zone of surface faulting; and (5) the epicenter of the main shock lies roughly midway along the zone of aftershock activity and thus seems to reflect bilateral faulting; the fracture propagates both northwest and southeast from the point of initial rupture.

As previously discussed, it seems unlikely that the dip of the fault plane is so shallow that the surface break represents the same fault plane as that indicated by the hypocenters of the larger aftershocks. Nor, in the light of the careful explosion calibration carried out by Hamilton (1970; this volume), is it likely that there is a major systematic error in the epicentral locations of the aftershocks.

The seeming lack of direct correlation between the trace of surface faulting and the aftershock distribution may be related to the complex local geology. It is obvious from the geologic map (fig. 7) that the San Jacinto fault zone in this region (as opposed to the San Jacinto fault itself) is not a simple fracture — not nearly so simple, for example, as the San Andreas fault in the Parkfield-Cholame area. The zone comprises many individual Quaternary breaks: northwest of the 1968 epicenters are the Buck Ridge, San Jacinto, and Coyote Creek faults, and to the southeast are the Superstition Hills and Superstition Mountain faults, as well as a possible extension of

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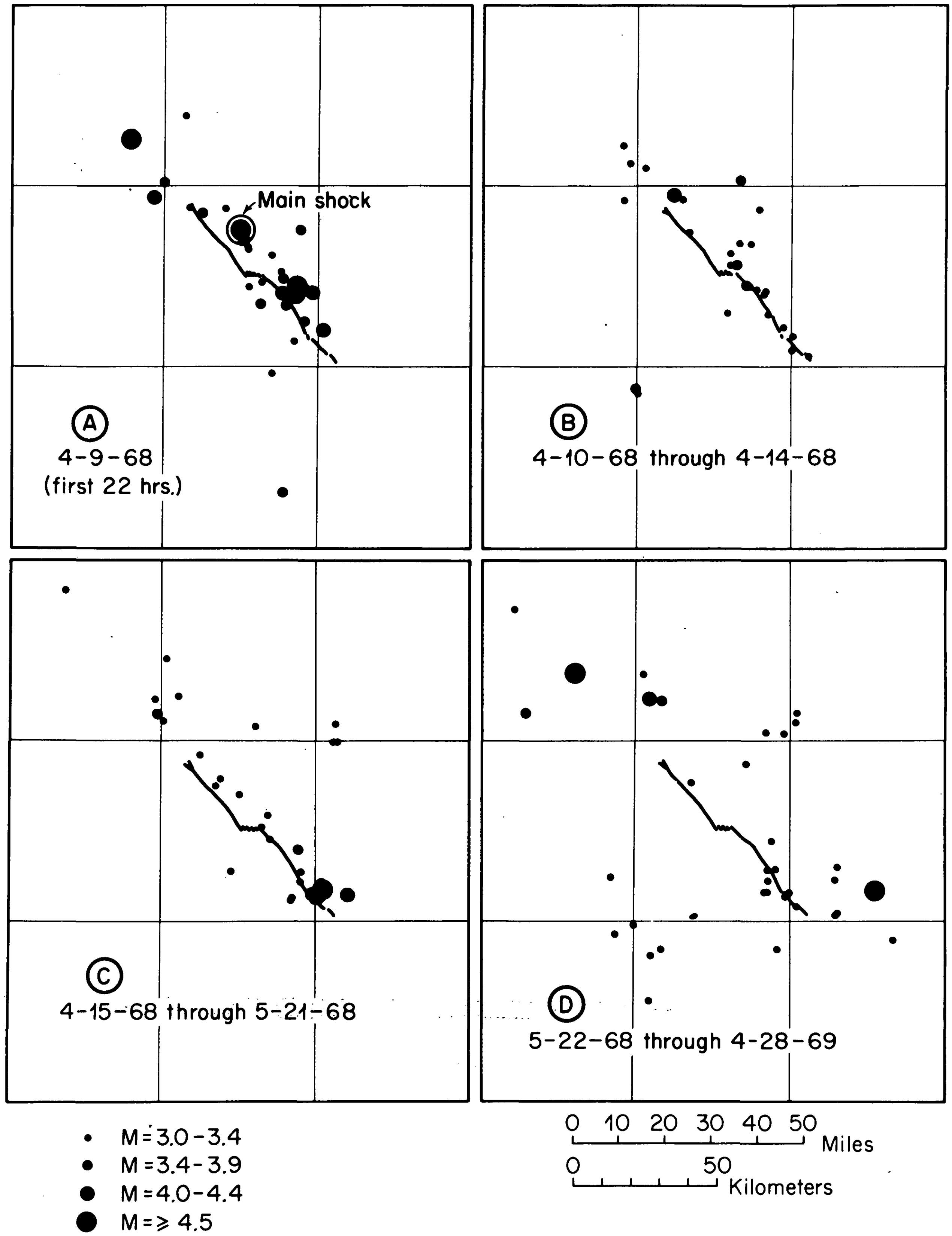

FIGURE 9. — Epicenters of figure 7, separated into four consecutive time periods (A to D) containing roughly equal numbers of shocks. Boundaries and coordinates of individual maps are the same as those of figure 7.

the Coyote Creek fault, which is represented by northwest-trending cracks across Highway 80, 4 km east of Plaster City, that were first observed in October of 1969 (fig. 7). Therefore it is not surprising that a major earthquake within the zone is a complex event, with aftershocks distributed over a number of individual breaks. Indeed, the aftershock zone of the 1968 event alines rather well with the center of the entire band of Quaternary faulting along the San Jacinto fault zone, whereas the surface faulting lies at the southwest edge of it. However, the question of why the surface faulting is apparently localized only along the margin of the fractured zone remains unanswered.

It is interesting that although the Borrego Mountain and Parkfield-Cholame earthquakes are of somewhat comparable magnitude and displacement, there are significant mechanical differences between them. In addition to the markedly different patterns of aftershock distribution, Max Wyss (oral commun., 1970) has pointed out that the apparent stress at all depths is higher at Borrego Mountain than at Parkfield-Cholame; average values for 12 events in the two localities differ by two orders of magnitude. Despite the fact that both earthquakes are low-stress-drop events (Wyss and Brune, 1968; Wyss and Hanks, this volume), the absolute stress at Borrego Mountain was considerably higher, which may be related to the markedly different patterns of aftershock activity.

The geological conditions at Parkfield-Cholame, typified by a relatively simple fault break that was perhaps "lubricated" by the presence of abundant serpentine in the fault zone (Allen, 1968), might logically be associated with earthquakes at relatively low levels of absolute stress. In the Borrego Valley area, on the other hand, the complex and discontinuous fault pattern might be visualized as necessarily demanding a relatively high absolute stress for breaking to be initiated, so that the faulting then occurred over a wider zone of pervasive fracturing.

The epicenter of the Borrego Mountain main shock lies roughly midway along the zone of aftershock activity (fig. 7) and thus seems to reflect bilateral faulting — with the fracture propagating both northwest and southeast from the point of initial rupture. This relation is in marked contrast to most other recent earthquakes in California, in which the initial epicenter has been at one end of the aftershock zone, thus reflecting unilateral faulting. Among these earlier earthquakes that have been well documented are the 1933 Long Beach earthquake (Richter, 1958), the 1940 Imperial Valley earthquake (Trifunac and Brune, 1970), the 1948 Desert Hot Springs earthquake (Richter and others, 1958), the 1952 Kern County earthquake (Richter, 1955), and the 1966 Parkfield-Cholame earthquake (McEvilly, 1966; Eaton, 1967). Indeed, the 1906 San Francisco earthquake is perhaps the only other large earthquake in California for which there is good evidence of bilateral faulting (Bolt, 1968).

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